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The effects of strain rate and temperature on the stress-strain rate behavior of Ti-6Al-4V alloy were investigated at 750-925 C and at strain rates of 10^{-5} to 10^{-4} s^{-1}. In the presence of strain hardening or strain softening, the stress-strain rate relation can no longer be represented by the conventional power-law formulation. The common assumption that a large value of the (apparent) strain rate sensitivity parameter is associated with a large amount of superplastic ductility is not tenable under test conditions where strain hardening or strain softening is noticeable.

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ANNUAL TECHNICAL REPORT

AFOSR GRANT NO. AFOSR-82-0081

FUNDAMENTAL INVESTIGATIONS OF FAILURE DURING SUPERPLASTIC FORMING PROCESS

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THE STRAIN RATE SENSITIVITY VALUES IN SUPERPLASTIC DEFORMATION

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SUMMARY

Fine grained superplastic alpha/beta ~~a/b~~ Ti-6Al-4V alloy was deformed in the temperature range 750-925°C and at strain rates of ~~10^{-5} to 10^{-4} s^{-1}~~ 0.00001 to 0.0001/s. The results indicate that an increase in the deformation temperature or a decrease in the deformation rate is followed by an increase in the value of strain hardening index (SHI). In such a situation, the stress-strain rate relation can no longer be represented by the conventional power law formulation without evaluating the effect of strain. The common assumption that a large value of the (apparent) strain rate sensitivity parameter is associated with a large amount of superplastic ductility is not tenable under test conditions where strain hardening or strain softening effect is noticeable.

Keywords: Titanium alloys; Mechanical behavior; Deformation mechanisms.

1. INTRODUCTION

Superplastic deformation (SPD) process, with its relatively large neck-free elongation has become an important technology for the forming process of the Ti-6Al-4V alloy in the past two decades. Generally, superplastic deformation possesses several unique characteristics (1) which differentiates it from the other conventional elevated temperature deformation mechanisms. One of the identifying characteristics of superplastic alloy is its high strain rate sensitivity (SRS) value. The

$$\sigma = K\dot{\varepsilon}^{m} \quad (1)$$

where m is the strain rate sensitivity (SRS) and K is a constant which depends on: temperature, rate controlling deformation mechanism, and metallurgical parameters such as grain size. Obviously, in cases where the strain hardening is not negligible, the above relation is no longer adequate. The true stress will vary not only as a function of the SRS, but also with the plastic strain that the material experienced during the deformation process. If the deformation is associated with strain hardening and/or strain softening, a realistic constitutive expression has to take that into account. The neglect of the strain hardening/softening process will lead to an apparent value of the strain rate sensitivity (ASRS).

Lee and Backofen [7] were first to publish results on the superplastic behavior of Ti and Zr alloys. From a large number of tests at 800-1000°C, they observed variation in the values of SRS parameter as a function of temperature. The maximum SRS value was about 0.8 at 950°C. Beyond that temperature, the SRS dropped rapidly. Lee and Backofen related the rapid drop in SRS value to the alpha/beta phase transformation. Another important observation, which were established in their work, was the relation between the SRS parameter and the elongation. According to their work, the larger the strain rate sensitivity value, the larger is the value of the neck free elongation of the specimen. Arieli and Rosen [8] also calculated the value of the the SRS in the range of 750-950°C. They found it to be equal to 0.5 in Ti-6Al-4V alloy. Ghosh and Hamilton [9,10] studied the change in the SRS

SRS is expected to have values equal to or larger then 0.5 for the manifestation of superplasticity. The high value of the SRS prevents the progression of the necking process during the plastic deformation. In region where the neck has already started, the local reduction of the cross sectional area causes an increase in the local strain rate. Consequently, an increase in the tensile stress is required in order to continue the deformation at the reduced cross sectional area. The higher the SRS, the higher is the local stress which would be required for neck formation. If the applied stress is not sufficient, the necking process would shift to another region. The above interpretation for neck formation in superplastic alloy is supported by the work of Morisson [3] and Wray [4]. They reported that multiple necks were observed simultaneously before one of the necks took control. Sagat and Taplin [5,6] observed an initiation of necking after only seventy percent strain. The significant necking which finally led to the failure, occured after several hundreds of percent of elongation. Hence, a high value of SRS helps to postpone the progress of catastrophic neck growth to a later stage of the deformation.

The strain hardening index (SHI), for most alloys which are deformed in the superplastic region, is found to be either zero or is assumed to be negligible. Accordingly, the stress which is required to maintain the deformation is mainly dependent on the level of the deformation rate and is independent of the instantaneous strain. Equation 1 describes the common power law relation between the steady state strain rate-$\dot{\varepsilon}$ and the applied true stress-σ during the superplastic deformation:

with deformation. The SRS was found to decrease as strain increased. The values of the SRS are found to be larger at the lower strain rate and for smaller grain size. Arieli, Maclean and Mukherjee [165] observed two distinct types of behavior of Ti-6Al-4V during superplastic deformation. At high strain rates and/or low temperatures and with larger grain sizes, the stress-strain curves showed strain softening. On the other hand at higher temperatures, lower strain rates and with finer grain size, strain hardening was observed.

This paper presents the results for mechanical deformation of a superplastic Ti-6Al-4V alloy in terms of the effect of temperature and strain-rate on strain-hardening or strain-softening phenomenon and on maximum attainable uniform elongation. A companion paper will present the results for microstructural investigation.

2. EXPERIMENTAL PROCEDURE

The material which was used in this investigation was Ti-6Al-4V, supplied by TIMET in the form of mill annealed sheets, 0.06 inches thickness. The chemical composition of the tested alloy is given in table 1.

TABLE 1. Chemical compsition of Ti-6Al-4V alloy

Al	V	Fe	O	N	Ti
0.73	3.99	0.099	0.085	0.003	Bal.

All specimens were produced by milling. The tensile axis of each specimen was parallel to the rolling direction of the sheet. The use of a close loop servohydraulic MTS tensile machine interfaced with a computer enabled us to maintain an approximate constant true strain rate during the test. A small positive pressure of purified argon gas was maintained inside the quartz test chamber during the entire test period.

Constant strain rate tests were conducted at 750, 800, 850, and 925°C and (at least) at four different strain rates: 10^{-5}, $2x10^{-5}$, $5x10^{-5}$ and 10^{-4} s^{-1}, in order to evaluate the stress-strain characteristics of Ti-6Al-4V under tensile load. The initial grain size, immediately before the application of the load, was 5 microns.

The curves in Fig. 1 through 4 depict the stress-strain relations obtained in these constant strain rate tests. Each curve, that is presented, is actually an average of several curves obtained at the same test conditions. These curves, demonstrate that either strain hardening or strain softening occurs during a tensile deformation. Softening occurs at 750°C at strain rate of 10^{-4}, $5x10^{-5}$ and $2x10^{-5}$ s^{-1}. At 800°C softening is obtained at strain rates of 10^{-4}, and $5x10^{-5}$ s^{-1}. Hardening, on the other hand, was observed at 800°C, $2x10^{-5}$ and $5x10^{-5}$ s^{-1} strain rates. At 925°C strain hardening was obtained in strain rates below $2x10^{-4}$ s^{-1}.

Another way to present the relation between the stress, the strain and the strain rate is shown in Fig. 5. These flow stress curves obtained at different constant strain are plotted as function of strain-rate and at three different temperatures. At low strain rates one observes strain hardening. Similarly the results show strain softening at higher strain rates. There is a transition from this strain hardening to strain softening behavior at a particular strain rate. This transition strain rate depends on temperature. As the temperature increases the transition from hardening (on the left side) to the softening (on the right side) tends to occur at higher strain rates. At the transition point, the stress remains unchanged as a function of strain during the deformation.

3. DISCUSSION

Much of the knowledge in superplasticity has been gathered from "well-behaved" materials such as Zn-Al eutectoid alloy [12], Sn-Pb eutectic alloy [13], and Al-Cu eutectic alloy [14]. The topological and metallographic features observed in these type of alloys are:

1. Stable microstructure without massive recrystallization
2. Extensive grain boundary sliding and negligible grain growth.
3. Grain shape remains approximately equiaxed during deformation.

These observations which are only a part of the total picture of microstructural aspects of superplasticity are outlined in order to illustrate the differences between the behavior of a "well behaved" superplastic alloy and that of the Ti-6Al-4V. It has been observed here and elsewhere [8,9,10,15], that mill-annealed Ti-6Al-4V during hot deformation possesses an unstable microstructure. The grains tend to grow rapidly. However Ti-6Al-4V is still considered as a commercially viable "superplastic alloy." Among the prerequisites which are traditionally required for Ti-6Al-4V for obtaining superplastic ductility is a strain rate which should be in a regime that provides a strain rate sensitivity (SRS) equal to or larger than 0.5. At present no investigation has attempted to put the effect of strain hardening or softening in Ti-6Al-4V on a quantitative basis. However, in Cu-P system Herriot et al. [16] reported on the differences between the measured apparent strain rate sensitivity in the presence of grain growth and the strain rate sensitivity calculated from superplastic deformation according to Eq. 1.

To evaluate the amount of the strain hardening or strain softening, a general equation which may be used is:

$$\sigma = K\dot{\varepsilon}^{m}\varepsilon^{h} \tag{2}$$

where m is the strain rate sensitivity (SRS) ε is the strain and h is the strain hardening index (SHI). This relation may also be expressed as a function of time, t, since:

$$\varepsilon = \dot{\varepsilon}t$$

hence,

$$\sigma = K\dot{\varepsilon}^{(m+h)}t^{h} \tag{3}$$

By assuming that both m and h remain unchanged at a given strain rate and a given temperature, the value of the strain hardening index during a constant strain rate test may be evaluated as:

$$h = d(\log\sigma)/d(\log t) = \Delta(\log\sigma)/\Delta(\log t) \tag{4}$$

Hence, by plotting the stress-time relations obtained in a constant strain rate test on a log-log plot, the strain hardening index can be evaluated graphically by measuring the slope. The values of the strain hardening index at 750, 800, 850 and 925°C are summarized in Fig. 6. The high values of SHI (h=0.58) were observed at the high temperature and the low strain rate: 925°C and 2×10^{-5} s^{-1}. However, even at lower temperatures the strain hardening index had values around 0.3 to 0.4. Negative values of strain hardening index were measured below a certain strain rate that depended on the testing temperature.

As was previously pointed out, the calculated apparent strain rate sensitivity, ASRS parameter will be different from the SRS, if either the strain hardening or the strain softening process occurs during the superplastic deformation. Thus the usage of Eq. 1 (analytically or graphically) in order to evaluate the SRS parameter for superplastic deformation should be done with care. According to Eq. 3 the value of the ASRS is:

$$\mathrm{ASRS} = m + h \tag{5}$$

where as stated earlier, "m" is the strain rate sensitivity and "h" is the strain hardening index.

If during the deformation, strain softening occurs, the ASRS will become smaller than the SRS parameter (i.e., h is negative). But, if strain hardening occurs, the ASRS will end up with a numerically higher value than the SRS parameter, m.

Without the assumption of the power law relation between the stress, the strain rate and the strain, Hart presented a general criterion for an homogeneous deformation, during tensile test [17]:

$$\gamma + m \geq 1 \tag{6}$$

Here

$$\gamma = 1/\sigma (d\sigma/d\varepsilon) \text{ and } m = (\dot{\varepsilon}/\sigma)(d\sigma/d\dot{\varepsilon}) \tag{7}$$

By definition, m is the SRS parameter and γ is equal h/ϵ. Therefore, the stability during the deformation is strongly dependent on the total deformation strain via, Eq. 6. Moreover, any increase in the SHI parameter will enhance the stability for deformation in the alloy through an increase in γ. In strain hardening materials, in which the flow stress is not sensitively dependent on strain rate, Hart's analytical criterion simply becomes:

$$\gamma \geq 1 \tag{8}$$

or

$$\epsilon \leq h \tag{9}$$

In such a situation strain may reach a maximum value that numerically equals the strain hardening index (Considere condition). However, in materials which are also sensitive to the strain rate, the limiting strain becomes:

$$\epsilon \leq h/(1-m) \tag{10}$$

Consequently, both the SHI and the SRS parameter control the amount of deformation that the alloy may experience before the onset of plastic instability. Increase in either h or m will result in the increase in the attainable strain before necking. This expression also implies that a certain amount of hardening is always necessary to maintain a valid value of strain. Furthermore, if strain softening process occurs, the SRS parameter should be larger than unity, or else, the limiting strain becomes negative ϵ (Eq. 10) in a tensile test implying immediate onset of instability. Generally, the value of the SRS does not exceed unity. Hence, hardening process must take place in order to avoid the necking during the plastic deformation. Therefore, if strain softening (negative value of h) occurs during the deformation, not only the stability of the deformation is reduced, as might be expected from Eq. 5, but more importantly it will be followed by instability immediately at the beginning of the deformation.

4. CONCLUSIONS

Ti-6Al-4V alloy, has several characteristic properties which distinguishes it from other "well behaved" superplastic alloys. An attempt to quantify the strain hardening index, as a function of temperature and strain rate, points out to the major roles that strain hardening and strain softening processes play during superplastic deformation. Furthermore, the stability (interms of absence of neck formation) obtained during the superplastic deformation seems to be more sensitive to variations in the strain hardening index and less to the apparent strain rate sensitivity. If strain softening occurs, the deformation is no longer stable and necking is expected to occur during the very early stage of plastic deformation.

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LIST OF FIGURE CAPTIONS

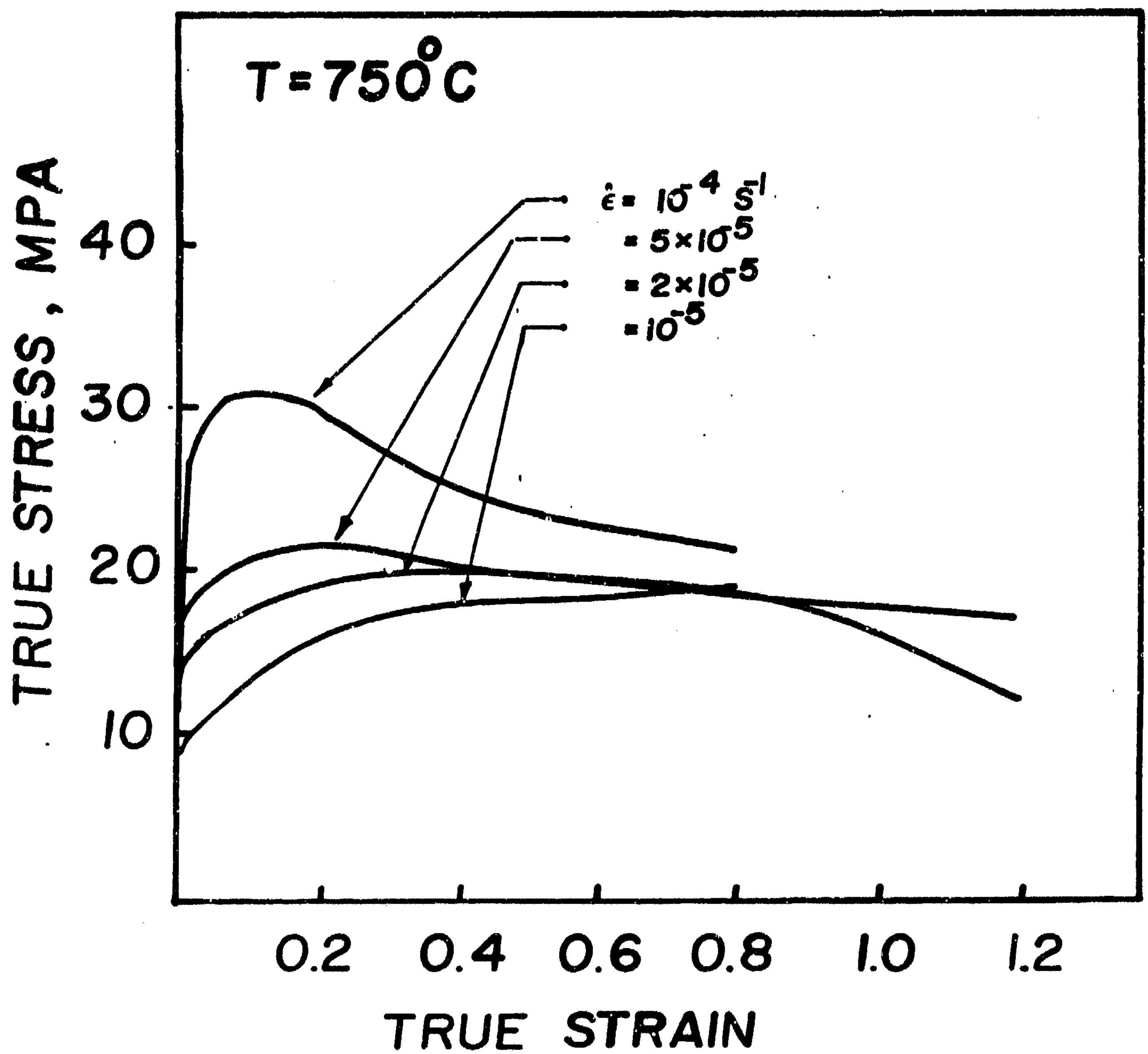

Figure 1 The effect of strain rate on the stress-strain behavior at 750°C.

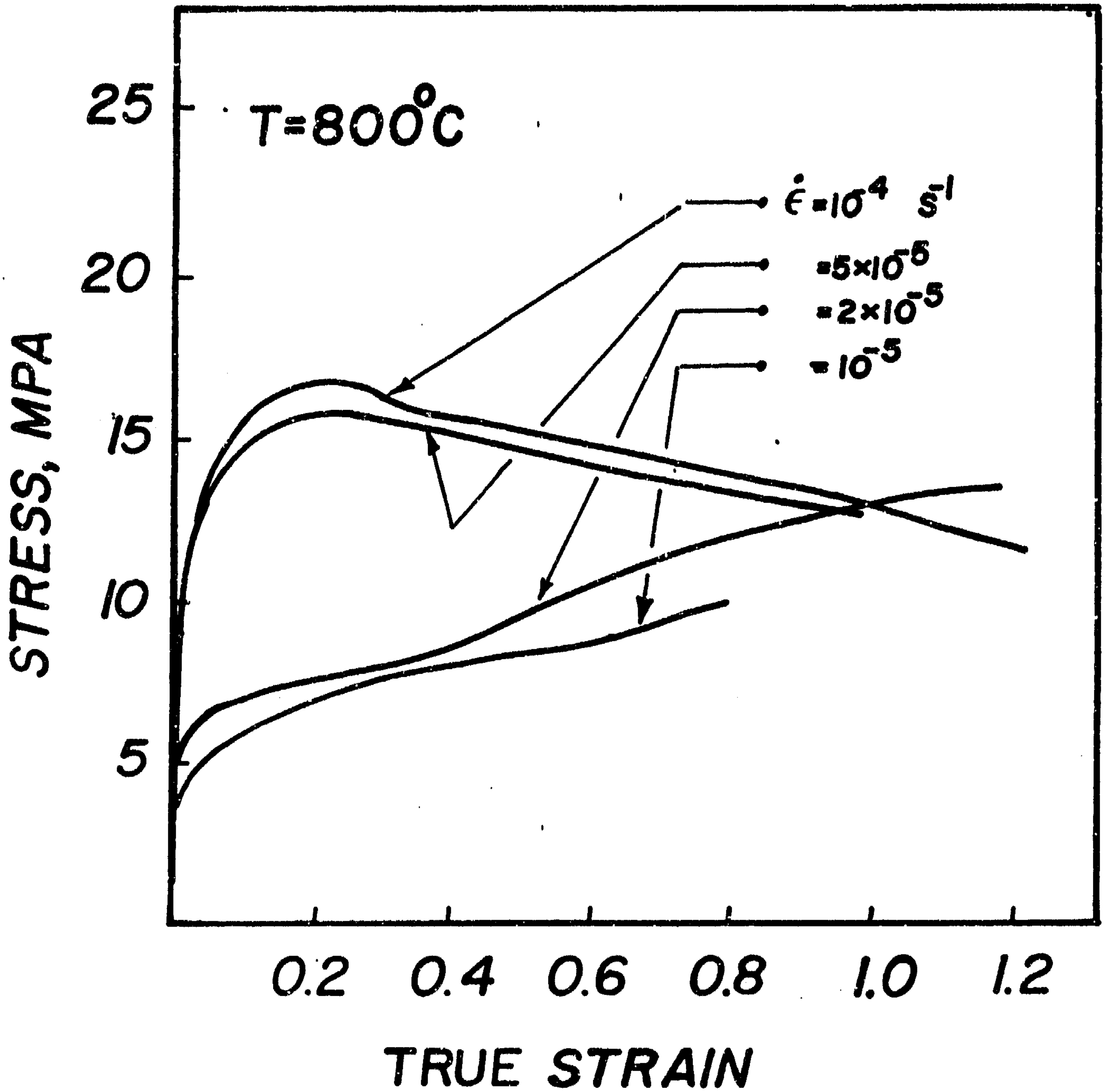

Figure 2 The effect of strain rate on the stress-strain behavior at 800°C.

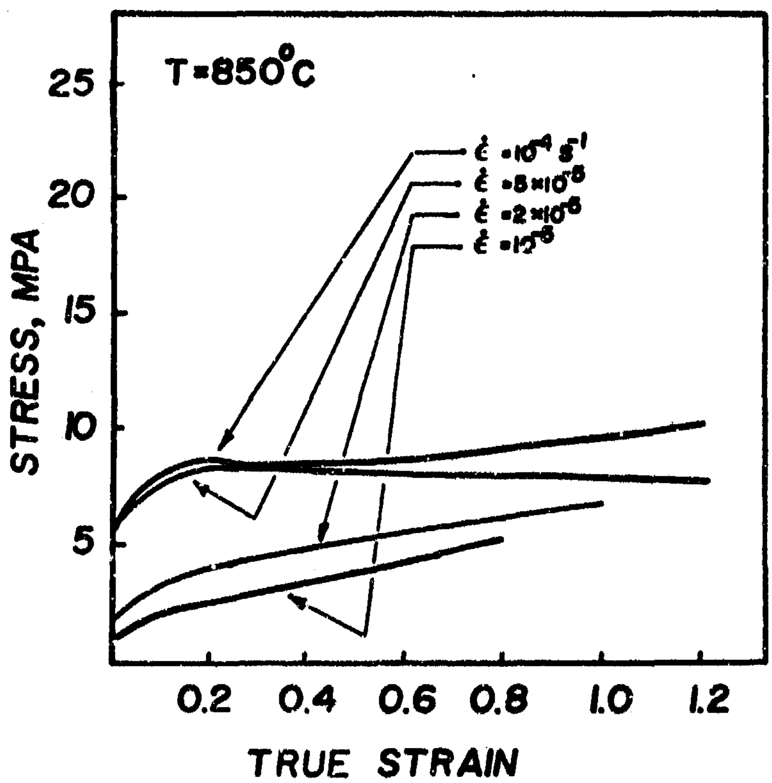

Figure 3 The effect of strain rate on the stress-strain behavior at 850°C.

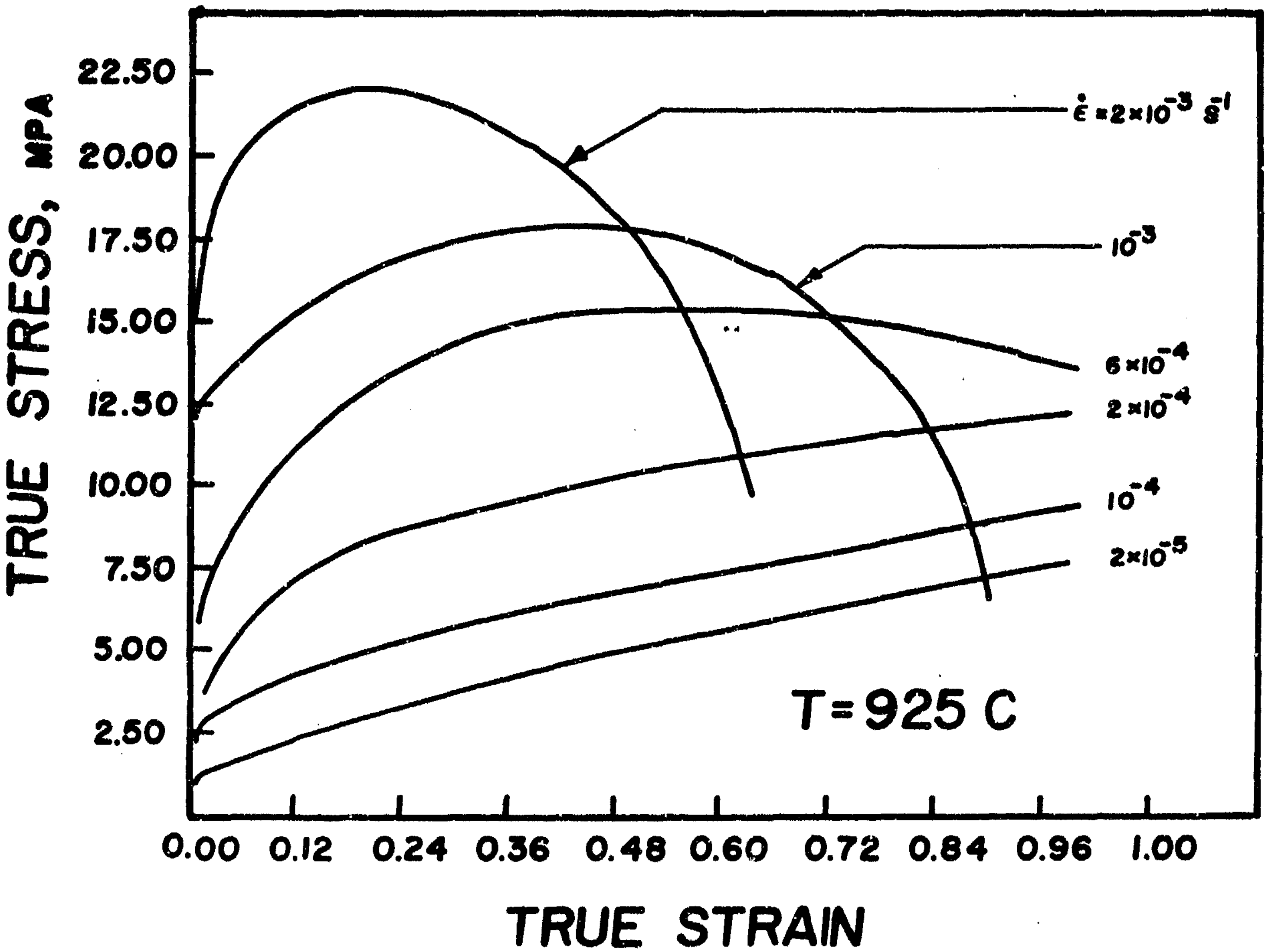

Figure 4 The effect of strain rate on the stress-strain behavior at 925°C.

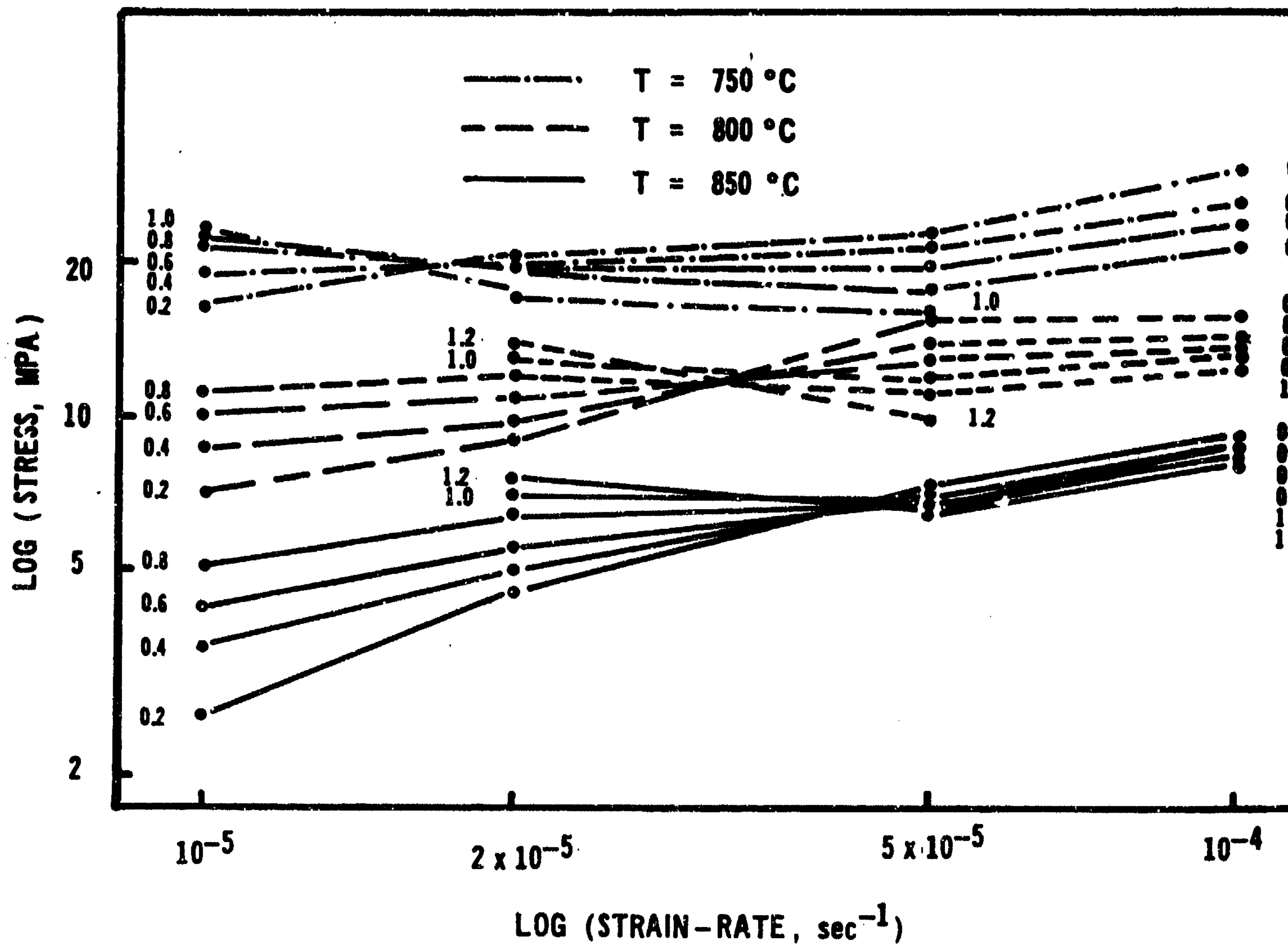

Figure 5 Log-Log plot of flow stress vs strain-rate at various levels of strain.

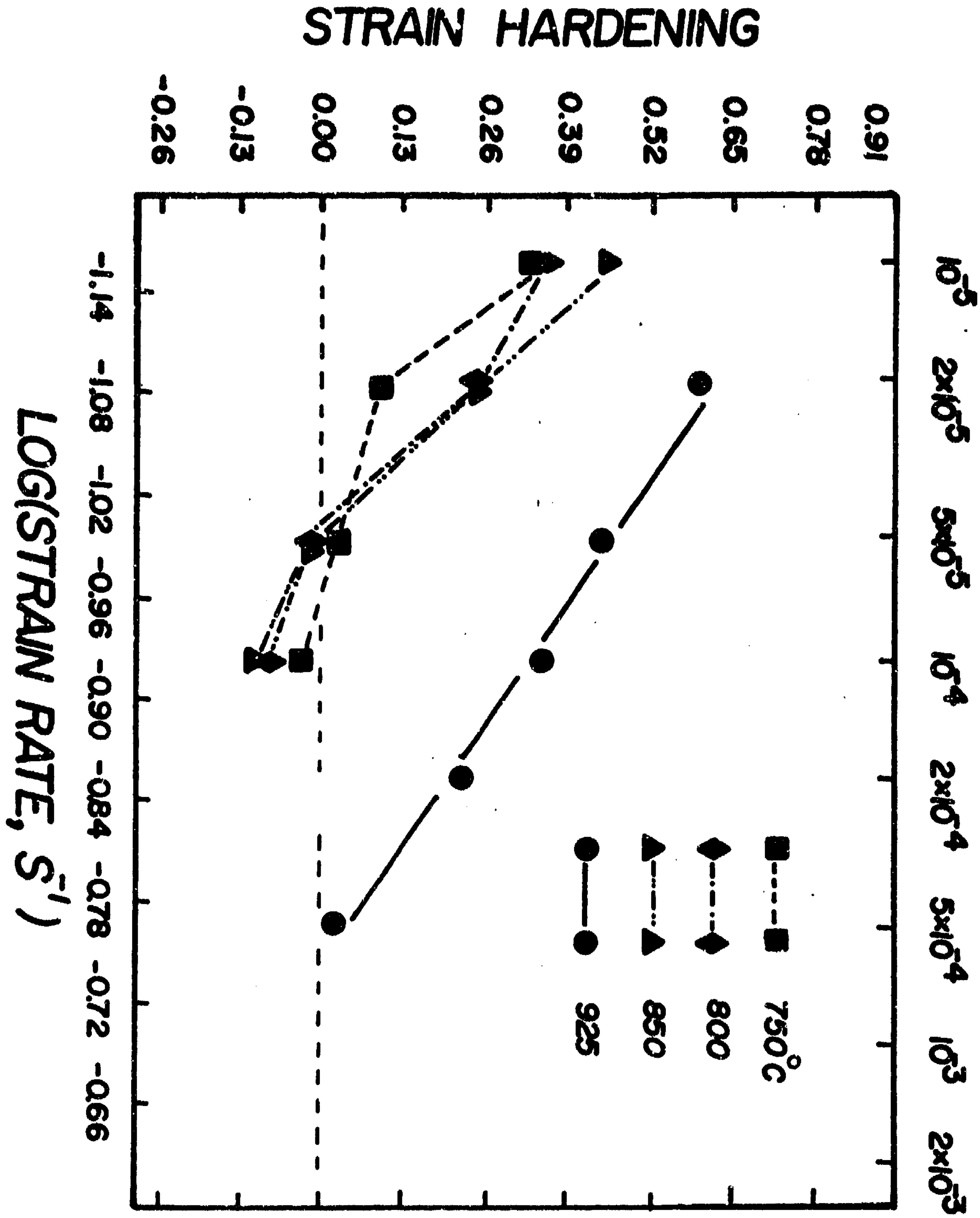

Figure 6 The effect of strain-rate and temperature on the strain hardening index.